



Near-surface wind field characteristics of the desert-oasis transition zone in Dunhuang, China

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Abstract: The desert-oasis transition zone (DOTZ) serves as a buffer area between the desert and oasis. Understanding its wind field characteristics is of great significance for the prevention and control of aeolian disasters in the oasis. In this study, we used meteorological data during 2013–2019 from the portable meteorological stations at five sites (site A on the edge of the oasis, sites B, C, and D in the DOTZ, and site O in the desert) in Dunhuang, China to analyze the near-surface wind field characteristics and their causes, as well as to reveal the key role of the DOTZ in oasis protection. The results showed that the mean wind speed, frequency of sand-driving wind, and directional variability of wind decreased from west to east within the DOTZ, and wind speed was significantly affected by air temperature. The terrain influenced the prevailing winds in the region, mainly from northeast and southwest. Only some areas adjacent to the oasis were controlled by southeasterly wind. This indicated that the near-surface wind field characteristics of the DOTZ were caused by the combined effects of local terrain and surface hydrothermal difference. At site D, the annual drift potential (DP) was 24.95 vector units (VU), indicating a low wind energy environment, and the resultant drift direction (RDD) showed obvious seasonal differences. Additionally, the DOTZ played an important buffering role between the desert and oasis. Compared with the desert, the mean wind speed in the oasis decreased by 64.98%, and the prevailing wind direction was more concentrated. The results of this study will be useful in interpreting the aeolian activity of the DOTZ in Dunhuang.

Keywords: desert-oasis transition zone; near-surface wind field; hydrothermal difference; sand-driving wind; aeolian environment; Dunhuang

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1 Introduction

Oasis is distributed on the edges of the desert and Gobi, and is a unique landscape in arid and semi-arid areas of the world. It provides valuable water resources and living spaces for the local people, plants, and animals (Wang et al., 2007; Liu et al., 2023b). The desert-oasis transition zone (DOTZ) refers to the narrow strip of land distributed around the periphery of the oasis, lying between the desert and oasis. It is also a link between the interaction and transformation of desert and oasis ecosystems (Zhang et al., 2017; Zhou et al., 2020; Sun et al., 2021), playing a vital role in maintaining the stability of oasis ecosystem and preventing the oasis from aeolian erosion (Zhao et al., 2008; Colazo and Buschiazzi et al., 2015; Ji et al., 2020). However, climate change and

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human activities cause frequent aeolian activity and increase the risk of desertification in some DOTZs, thereby weakening their protective and buffering effects on the oasis (An et al., 2023). Therefore, understanding the aeolian environment of the DOTZ and preventing and controlling aeolian disasters are necessary to ensure the ecological security of the oasis. Previous studies on the DOTZ have mainly focused on soil physical and chemical properties (Zhang et al., 2018a; Liu et al., 2020b), plant communities (Potchter et al., 2008; Ma et al., 2009; Ainiwaer et al., 2020; Zhou et al., 2020), microclimate (Zhang and Zhao, 2015; Mao et al., 2016), hydrology (Zhao and Zhao, 2014; Yin et al., 2021), etc. Although many studies have comprehensively evaluated the ecological effects of the DOTZ, research on its aeolian environment is relatively scarce.

Near-surface wind field characteristics, such as wind speed and wind direction, are key factors in aeolian environmental research; they not only control the development of aeolian geomorphology but also have a profound impact on the transport process of sand flow structures (Rendig, 1948; Wang et al., 2015). Many researchers have used near-surface wind field characteristics to evaluate regional aeolian environmental status and evolution laws (Xing et al., 2008; Zu et al., 2008; Zhang et al., 2023). For example, Zu et al. (2008) studied the near-surface wind field of the Taklimakan Desert, China and found that the prevailing wind directions in the desert were northeast (NE) and northwest (NW), and the local wind regime showed unimodal or bimodal features. Liu et al. (2019) supplemented this study and indicated that wind speed has decreased the most in spring and in the eastern part of this desert since 1965, and the change in the drift potential (DP) was mainly controlled by the winds from NW, north (N), and NE. Cui et al. (2019) analyzed the temporal variation of the near-surface wind field of the Mu Us dune field, China and revealed that wind speed generally decreased during 1960–2014, especially in autumn and winter, and the DP also reduced. These studies have focused on the aeolian environment of large-scale regions, such as deserts. However, small-scale regions with special landscapes have rarely been studied, even though they exhibit significant differences in near-surface wind field characteristics compared with large-scale regions. The near-surface wind field in large-scale regions is primarily controlled by atmospheric circulation and the surrounding terrain, which affect the aeolian environment and local landforms (Sivakumar, 2007; Zu et al., 2008; Dong et al., 2009). However, the near-surface wind field in small-scale regions is mainly influenced by local terrain and hydrothermal characteristics, which in turn affect local aeolian activity characteristics (Radünz et al., 2020). Changes in aeolian activity characteristics may threaten aeolian disasters; therefore, the research in these regions should focus on understanding these characteristics and taking preventive measures accordingly (Dong et al., 2010).

Dunhuang is a historic city in Gansu Province of China and an important hub on the Silk Road; it has world-class cultural and natural heritage sites, such as the Mogao Grottoes, Mingsha Mountain, and Yardangs, attracting many tourists and researchers from all over the world (Qu et al., 1997; Zhang and Xie, 2017; Dong et al., 2021). The natural landscape of Dunhuang consists of the desert, oasis, and DOTZ, of which the DOTZ has a decisive impact on the urban development and landscape patterns of Dunhuang (Su et al., 2007; Ma et al., 2009; Chen et al., 2023). The DOTZ is also a special landscape between the desert and oasis, which can effectively protect the oasis and prevent desert aeolian invasion (Zhang et al., 2017; An et al., 2023). In recent years, Dunhuang has faced severe ecological problems due to climate change and human activities, which have caused frequent strong winds and sandstorms in this region, leading to the shrinkage of oasis and the intensification of desertification, thereby threatening the safety of local people and natural and cultural heritage (Xu et al., 2006; Guo et al., 2011; Pan et al., 2023). In this situation, the DOTZ plays an important role. It is not only a natural barrier between the desert and oasis, restraining the invasion of aeolian activity in Dunhuang, but also a preferred place for future oasis expansion and desert transformation, providing infinite possibilities for the ecological civilization construction of Dunhuang in the future (Xing et al., 2008; Zhang et al., 2015a; Mao et al., 2019). Therefore, studying the near-surface wind field characteristics of the DOTZ in Dunhuang is key to explore the aeolian environment in this area and is also a necessary means to reveal the protective effect of the DOTZ on the oasis. Many researchers have studied the aeolian

environment in Dunhuang. For example, Shen et al. (2005) used the observational data of the Gobi desert and oasis in Dunhuang to conduct a detailed comparative analysis of the main wind erosion factors affecting dust emissions. Their study showed that different types of croplands had different dust emission rates, among which those of plowed croplands were hundreds of times higher than those of the Gobi desert. Li et al. (2013) evaluated the responses of three typical plant species to wind erosion in the shrub zone of the Mogao Grottoes in Dunhuang, and indicated that the best way to configure shrubs to resist wind erosion is to design two parallel rows perpendicular to the main wind direction. Zhang et al. (2016) verified the development of a star dune on the Mingsha Mountain in Dunhuang using long-term observational and monitoring data. Their results showed that topographic barrier was the main reason for the formation of the complex mega-dunes. In addition, some scholars have conducted in-depth studies on landscape changes (Zhang et al., 2018b) and dynamic dune changes (Ding et al., 2020; An et al., 2022) in the desert and oasis of Dunhuang.

Previous studies have yielded many important results regarding the aeolian environment in the desert and oasis of Dunhuang. However, owing to a lack of comprehensive meteorological data, the study regarding the aeolian environment of the DOTZ in Dunhuang was largely overlooked. The knowledge gap has limited our understanding of aeolian processes in the DOTZ and their effects on oasis protection. This has compromised the effectiveness of wind-blown sand control measures in local areas. Hence, we conducted a detailed analysis of the near-surface wind field in the DOTZ based on observed meteorological data to fill this gap. Furthermore, exploring the influence of the near-surface wind field characteristics of the DOTZ in Dunhuang on the aeolian environment not only helps to protect the oasis but also provides valuable insights for sand-blown control strategies in other similar areas.

The specific aims of this study were to (1) analyze the near-surface wind field characteristics and causes of the DOTZ in Dunhuang to systematically evaluate its aeolian environment; and (2) reveal the key role of the DOTZ in oasis protection. The results of this study will be useful for the interpretation of aeolian activity in the DOTZ and provide guidance for the prevention and mitigation of aeolian sand hazards in the oasis of Dunhuang.

2 Materials and methods

2.1 Study area

Dunhuang is an important segment of the Hexi Corridor, located in the northwest of China (92°15′–95°30′E, 39°40′–41°35′N; Fig. 1a), with an area of approximately 3.12×10^4 km². It is flanked by the Mingsha Mountain to the south (S) and the oasis to the N, where the elevation is low and forests and towns are distributed. The terrain decreases from S to N, with a mean elevation of approximately 1100 m. The climate is continental and arid, with scarce and uneven precipitation throughout the year. The mean annual precipitation is less than 40 mm, and the mean annual evaporation is as high as 2488 mm. Strong winds and sandstorms are frequent and intense, particularly in spring. Natural vegetation is sparse and dominated by *Alhagi sparsifolia*, *Haloxylon ammodendron*, *Caragana korshinskii*, and *Populus euphratica*.

2.2 Data sources

The meteorological data from 2013 to 2019 were obtained from five portable meteorological stations located in the desert, oasis, and DOTZ of Dunhuang. The desert and oasis each had one portable meteorological station, whereas the DOTZ had three stations. All portable meteorological stations were produced by HOBO, an American company based in Onset. To evaluate the near-surface wind field characteristics and causes of the DOTZ and reveal its key role in oasis protection, we selected five sites according to the locations of the five portable meteorological stations. Specifically, site A was on the edge of the oasis; sites B, C, and D were within the DOTZ; and site O was located in the desert. The vegetation coverage of each site declined markedly along the oasis–desert gradient (Fig. 1b1–b3). All the portable meteorological

stations were erected at a height of 2.0 m above the ground surface, surrounded by flat and open terrain. The wind cup and wind vane installed on the portable meteorological stations were used to measure the wind speed and direction from 16 directions, including N, north-northeast (NNE), NE, east-northeast (ENE), east (E), east-southeast (ESE), southeast (SE), south-southeast (SSE), S, south-southwest (SSW), southwest (SW), west-southwest (WSW), west (W), west-northwest (WNW), NW, and north-northwest (NNW). The data were collected at 10-min intervals and averaged daily, with accuracies of 0.10 m/s and 3°. We used the meteorological data at these sites from a complete year (from 1 January 2016 to 31 December 2016) to calculate the mean air temperature, mean wind speed, sand-driving wind, and DP. To ensure data quality, we removed outliers based on previous studies in this area (Zhang et al., 2015a; Zhang et al., 2017; An et al., 2023) and used linear interpolation with the meteorological data for other years in the desert, oasis, and DOTZ to fill in missing values. Furthermore, we also assessed the data quality.

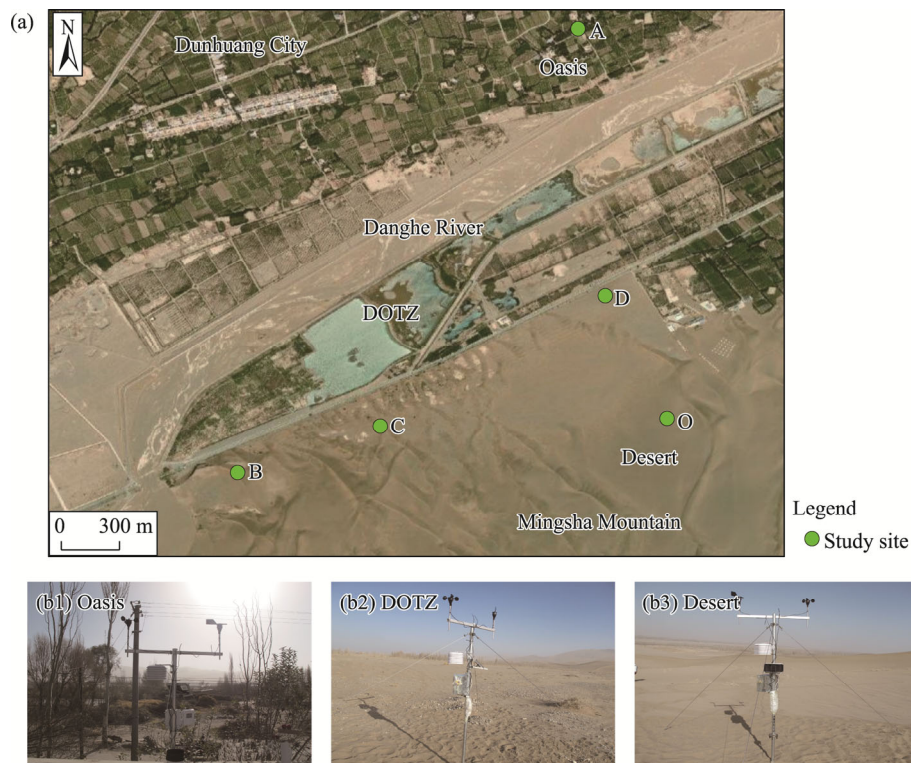


Fig. 1 Overview of the desert-oasis transition zone (DOTZ) in Dunhuang and locations of the five study sites (a), as well as photos showing the landscapes of portable meteorological stations (b1–b3). The upper figure is based on the World Imagery (WGS84) data from Esri, Maxar, and Earthstar Geographics.

2.3 Calculation of the data

Using air temperature and wind data from the portable meteorological stations, we calculated the mean wind speed, mean air temperature, and sand-driving wind in the desert, oasis, and DOTZ at different time scales. We also estimated the DP of each site in the DOTZ across time scales.

The threshold wind speed for sand movement, generally referred to as the sand-driving wind, is an important parameter that reflects the wind conditions in a region (Zhang et al., 2012; Xiao et al., 2021). The desert, oasis, and DOTZ in Dunhuang have small spatial scales, and there is no significant difference in the threshold sand-driving wind speed among them (Zhang et al., 2017; An et al., 2023). Therefore, we set the threshold sand-driving wind speed to 5.00 m/s for all sites in this study.

DP is a key parameter that indicates the potential maximum sand transport rate expressed in

vector units (VU), which can reflect wind energy environment in a specific area (Zu et al., 2008; Pye and Tsoar, 2009; Hereher, 2018; Wang et al., 2022). The formula proposed by Fryberger and Dean (1979) was used for calculating DP:

$$DP = V^2 (V - V_t) t, \quad (1)$$

where DP is the drift potential, which is expressed in vector units (VU); V is the sand-driving wind speed at a height of 2 m (m/s); V_t is the threshold sand-driving wind speed (m/s); and t is the duration of sand-driving wind, which is usually calculated by frequency (%). The classification criteria for the wind energy environment are listed in Table 1.

The resultant drift potential (RDP; VU) and resultant drift direction (RDD; °) are the vector sums of the DP and direction for each azimuth, respectively. The formulas are as follows (Fryberger and Dean, 1979):

$$RDP = (C^2 - D^2)^{\frac{1}{2}}, \quad (2)$$

$$RDD = \text{Arctan} \left(\frac{C}{D} \right), \quad (3)$$

$$C = \sum (VU) \sin \theta, \quad (4)$$

$$D = \sum (VU) \cos \theta, \quad (5)$$

where C and D are the parameters for calculating RDP and RDD, respectively; and θ is the angle measured clockwise from 0° (N), with the unit of °.

In addition, the ratio of RDP to DP, namely RDP/DP, is regarded as an important indicator for describing the directional variability of wind (Al-Awadhi et al., 2005; Zhang et al., 2015b). The classification criteria for directional variability of wind are listed in Table 1.

Table 1 Classification criteria of wind energy environment and directional variability of wind

DP	Wind energy environment	RDP/DP	Directional variability
>400 VU	High	<0.3	High
200–400 VU	Intermediate	0.3–0.8	Intermediate
<200 VU	Low	>0.8	Low

Note: The classification criteria are based on Fryberger and Dean (1979). DP, drift potential; VU, vector units; RDP, resultant drift potential; RDP/DP, the ratio of RDP to DP, which is regarded as an important indicator for describing the directional variability of wind.

2.4 Statistical analysis

We calculated all parameters using Excel, according to the above-mentioned formulas. Linear regression analysis was conducted to explore the correlation between mean air temperature and mean wind speed within the study area, and statistical analysis was performed using Origin 2021 (OriginLab, Northampton, USA). Figures were created using ArcMap 10.7 (Esri, Redlands, USA), Surfer 15 (Golden Software, Golden, USA), and Origin 2021.

3 Results and discussion

3.1 Mean air temperature

Figure 2 shows the mean annual air temperature of the DOTZ and surrounding sites. The mean annual air temperature of the desert, oasis, and DOTZ ranged between 11.4°C and 13.0°C, with the highest and lowest air temperature values located in the desert and DOTZ, respectively. Moreover, the central part of the DOTZ was the low mean annual air temperature center of this region. In addition, most areas in this region had a mean annual air temperature lower than 13.0°C and exhibited a small spatial variation, with the mean annual air temperature difference of 1.6°C. However, from the density of the isotherms in the study area it can be seen that the isotherms between the desert and DOTZ were denser than those between the oasis and DOTZ. This

indicates that the mean annual air temperature difference between the oasis and DOTZ was smaller. Moreover, the increase of mean annual air temperature relative to the low mean air temperature center was less than 0.5°C .

The distribution characteristics of local mean annual air temperature were determined by the combined effects of the oasis effect, urban heat island effect, and other factors. Generally, the oasis effect, which resulted from the hydrothermal difference between the desert and oasis surfaces, caused heat transfer from the desert to the oasis (Li et al., 2016; Bie et al., 2020; Liu et al., 2020a). This has led to a significant reduction in air temperature of the oasis relative to that of the desert (Liu et al., 2005). However, the rapid urbanization process in Dunhuang, accompanied by a series of other human activities, such as population growth and industrial activities, influenced the hydrothermal difference between the desert and oasis (Oke, 1982; Jia et al., 2023). The urban heat island effect exacerbated this contrast, considerably weakening the oasis effect and making the air temperature of oasis declined less noticeable (Ayanlade, 2016; Kasniza Jumari et al., 2023). Furthermore, the DOTZ was adjacent to the Danghe River (Fig. 1), and the regulatory effect of the river slowed the increase rate of local air temperature, making it the coldest area in the region (Gupta et al., 2019; Feng et al., 2023). This caused the near-surface air pressure in the DOTZ to be higher than that in the surrounding areas, and thus formed convection owing to the uneven pressure gradient, which in turn generated an airflow that diverged from the DOTZ to the surrounding areas (Zhang et al., 2017).

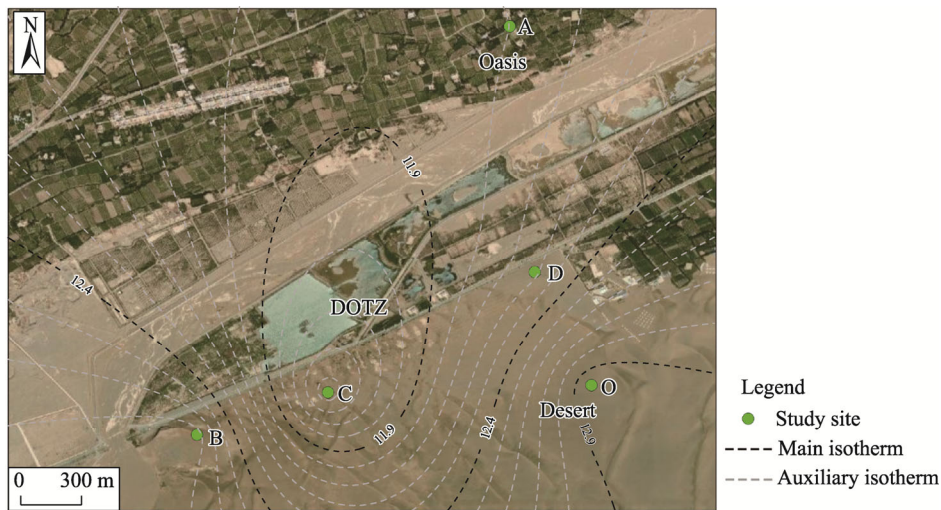


Fig. 2 Isoline map of mean annual air temperature in the study area. The dashed lines of different colors all represent the mean annual air temperature values, with the black dashed lines indicating the main isotherms at the interval of 0.5°C , and the gray dashed lines showing the auxiliary isotherms at the interval of 0.1°C . The figure is based on the World Imagery (WGS84) data from Esri, Maxar, and Earthstar Geographics.

3.2 Mean wind speed

As shown in Figure 3, wind speed showed a gradually decreasing trend from W to E in the DOTZ, with a large spatial difference. The mean annual wind speed at site B, i.e., the westernmost site in the DOTZ, was 3.39 m/s , which was 1.64 m/s higher than that at site D (1.75 m/s), i.e., the easternmost site in the DOTZ. This was related to the distribution characteristics of local air temperature. The results of the previous section showed that hydrothermal difference significantly affected the distribution characteristics of air temperature in the desert, oasis, and DOTZ, as well as the near-surface wind field environment. Compared with site B, site D was closer to the oasis, and the regulatory effect of the oasis lowered its hydrothermal difference and wind speed, which was consistent with the results of Liu et al. (2020a). Moreover, the mean annual wind speed in the region exhibited large spatial variation. Specifically, the mean annual wind speed in the desert

reached 2.97 m/s, but it was only 1.04 m/s in the oasis. Wind speed was an important indicator for characterizing the dynamic wind environment in a region (Li et al., 2019). This phenomenon was influenced by both the effect of the oasis-desert microclimate and the blocking effect of the DOTZ. These two factors worked together to effectively weaken the wind speed, resulting in a 64.98% reduction in the mean annual wind speed during this process (Zhao et al., 2008; Chen et al., 2015; Liu et al., 2018; An et al., 2023).



Fig. 3 Isoline map of mean annual wind speed in the study area. The dashed lines of different colors all represent the mean annual wind speed values, with the black dashed lines indicating the main contours at the interval of 0.50 m/s, and the gray dashed lines showing the auxiliary contours at the interval of 0.10 m/s. The figure is based on the World Imagery (WGS84) data from Esri, Maxar, and Earthstar Geographics.

To further explore the relationship between wind speed and air temperature, we fitted the mean monthly wind speed and mean monthly air temperature of sites A, D, and O located in the oasis, DOTZ, and desert, respectively (Fig. 4a). The results showed that the correlation coefficient of the mean monthly wind speed and mean monthly air temperature in the oasis was only 0.09, while the correlation coefficients between them in the desert and DOTZ were both higher than 0.50, and wind speed showed a slight increase trend with the increase of air temperature. This indicated that there was no obvious correlation between wind speed and air temperature from the desert to the oasis. After fitting the mean monthly wind speed and mean monthly air temperature of sites B, C, and D located in the DOTZ (Fig. 4b), we found that the correlation coefficients were 0.69, 0.88, and 0.54, respectively, indicating that the wind speed in the DOTZ tended to increase with increasing air temperature, with site C being the most significant. Although site D displayed the highest slope in the fitting function, its degree of fitting was the poorest, likely because of its proximity to the oasis.

One plausible explanation for these observations is that both the local microclimates of the desert and oasis influenced the wind speed, and the oasis deepened the differences between them through modulation (Mao et al., 2017a; Cao et al., 2020; Liu et al., 2023c). This also suggested that a phenomenon similar to the "wind-heat synchronization" in the desert interior occurred in the DOTZ (Zu et al., 2008; Mao et al., 2017b). Thus, the hydrothermal difference was the main factor causing the changes of wind speed in the DOTZ. In contrast, although the wind speed between the oasis and desert decreased from the desert, it exhibited no significant correlation with air temperature. Consequently, the DOTZ emerged as the primary factor determining the wind speed. This underscored the effectiveness of the DOTZ in mitigating potential aeolian hazards (Wang et al., 2020; An et al., 2023).

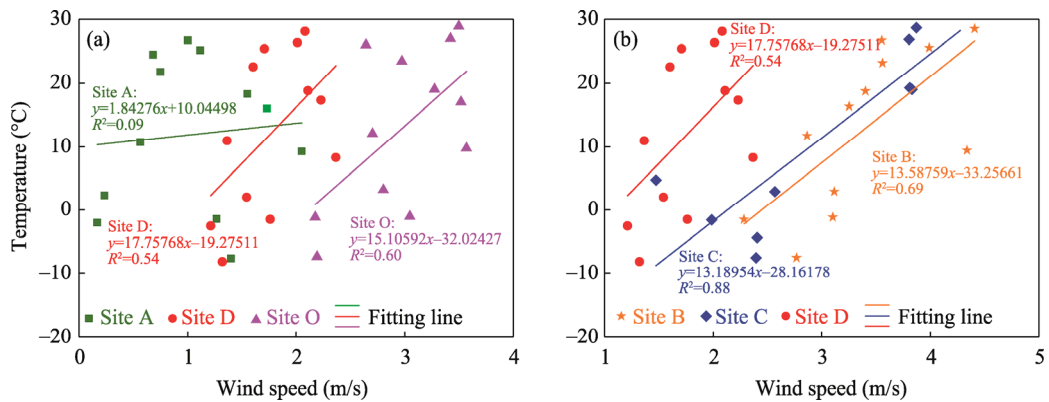


Fig. 4 Linear regression analysis between mean monthly wind speed and mean monthly air temperature at sites A, D, and O from north to south (a) and at sites B, C, and D from west to east (b)

3.3 Sand-driving wind

Figure 5 shows the sand-driving wind roses of the desert, oasis, and DOTZ in Dunhuang. It was observed that in the DOTZ, the frequency of sand-driving wind decreased gradually from W to E. According to the statistics, at site B, i.e., the westernmost site in the DOTZ, the frequency of sand-driving wind was 29.80%, whereas at site D, i.e., the easternmost site in the DOTZ, the frequency of sand-driving wind was only 6.00%. Additionally, the frequency of sand-driving wind in the DOTZ differed significantly from those in the desert and oasis along the N–S direction. From S to N in the study area, the annual number of sand-driving wind events in the desert, DOTZ, and oasis was 10,676, 3007, and 1842, respectively. Compared with the desert, the annual number of sand-driving wind events in the oasis decreased by nearly 82.75%, indicating that the DOTZ played an important buffering role in oasis protection and could effectively reduce the intensity of aeolian activity in the region.

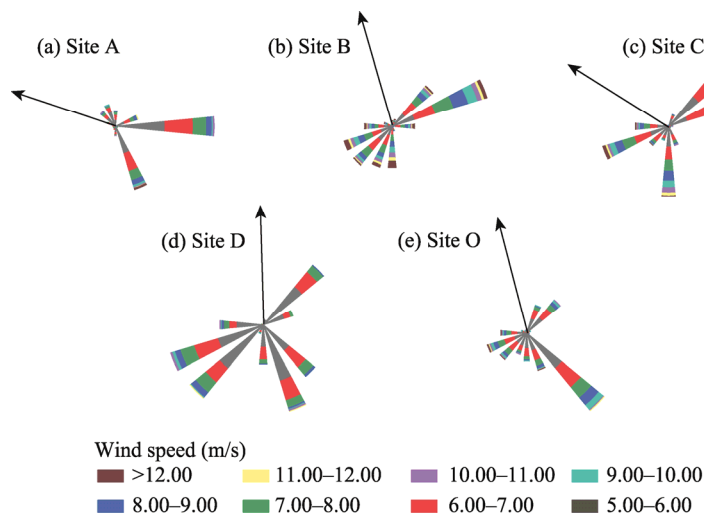


Fig. 5 Sand-driving wind roses in the study area. (a), site A; (b), site B; (c), site C; (d), site D; (e), site O. The arrow indicates the resultant drift direction (RDD).

The sand-driving wind direction in the desert, oasis, and DOTZ was also an indispensable indicator for evaluating the local near-surface wind field environment. As the local air flow was mainly driven by hydrothermal difference between the underlying surfaces, this air flow diverged from the DOTZ to the desert and oasis. However, the actual wind direction was more complex

due to the influence of local terrain (Radünz et al., 2020; Zhang et al., 2023). The vegetation in the DOTZ and the forests and buildings in the oasis greatly increased the roughness of the underlying surfaces, which had a significant weakening effect on the wind speed (Bruno and Fransos, 2015; Zhao et al., 2019; Li et al., 2023), further resulting in very little northwesterly wind impact in most areas of the DOTZ. In addition, the sandy hills on the S side blocked the wind in that direction. As a result, only site D at the eastern end of the DOTZ was more affected by the southeasterly wind, whereas the other sites were mainly influenced by the winds from NE and SW. However, because site D was closer to the oasis, the disturbance and obstruction of vegetation to the near-surface air flow made it less affected by the northeasterly wind (Pang et al., 2022). At the same time, the good blocking effect of the DOTZ has led to a single prevailing wind direction for both the desert and oasis (An et al., 2023), where the former was mainly controlled by the southeasterly wind and the latter was mainly influenced by the easterly wind.

The differences in wind direction between the DOTZ and its adjacent areas were reflected in the frequency distribution of wind direction at each site. Table 2 not only presents the frequency of two groups of wind directions (E+SE+SSE and S+SW+WSW) extending across sites A, D, and O from N to S in the study area, but also shows the frequency of two groups of wind directions (NE+ENE and SW+WSW) spanning across sites B, C, and D from W to E in the DOTZ. The results indicated a significant decrease in the frequency of easterly wind from N to S in the study area, whereas the frequency of southerly wind changed in the opposite direction. From W to E in the DOTZ, the frequency of northeasterly wind decreased, whereas that of southwesterly wind increased significantly.

Table 2 Changes in prevailing wind directions in the study area

Site	Frequency of wind direction (%)		Site	Frequency of wind direction (%)	
	E+SE+SSE	S+SW+WSW		NE+ENE	SW+WSW
A	58.90	5.21	B	36.37	23.99
D	28.20	41.20	C	40.65	21.33
O	36.30	26.70	D	19.49	34.15

Note: E, east; SE, southeast; SSE, south-southeast; S, south; SW, southwest; WSW, west-southwest; NE, northeast; ENE, east-northeast.

3.4 DP

According to the previous analysis, the wind energy environment at site D between the desert and oasis can reflect the situation of the DOTZ. This also revealed the key role of the DOTZ in oasis protection. Therefore, based on the annual and seasonal variations of DP from 2013 to 2019 (Fig. 6), we can see that the region had a low annual DP of 24.95 VU, indicating a low wind energy environment. The seasonal DP ranged from 2.98 to 9.47 VU, with the highest DP in spring (at 9.47 VU) and the lowest in winter (at 2.98 VU). Both the DP in spring and winter belonged to a low wind energy environment, indicating that the seasonal difference of DP in the DOTZ was not significant. In addition, the RDP at site D did not show clear seasonal differentiation, and the difference between the maximum and minimum values was only 2.32 VU. However, the RDD showed significant seasonal differences, with values of 8.0° and 37.5° in summer and winter, respectively, and 338.4° and 356.7° in spring and autumn, respectively. This indicated that the DOTZ showed a southwesterly sand drift direction in summer and winter, whereas a southeasterly sand drift direction in spring and autumn.

To delve deeper into the wind direction combinations within the DOTZ, we analyzed the inter-annual and seasonal trends of RDP/DP at sites B, C, and D. Figure 7 depicts the changes of RDP/DP in the DOTZ at different time scales. The analysis revealed that RDP/DP gradually increased from W to E in the DOTZ. At site B, i.e., the westernmost site in the DOTZ, the annual RDP/DP was 0.23, indicating high directional variability, whereas at site D, i.e., the easternmost

site in the DOTZ, the annual RDP/DP was 0.43, indicating intermediate directional variability. In addition, significant differences were observed in the seasonal distribution of RDP/DP in the DOTZ. Sites B and C displayed large seasonal variations in directional variability, whereas directional variability at site D remained almost constant in all seasons. For instance, the RDP/DP at site C was 0.22 in summer and 0.46 in autumn, indicating high and intermediate directional variability, respectively. But the RDP/DP at site D remained between 0.30 and 0.60 in all seasons, indicating intermediate directional variability. In general, the directional variability in the DOTZ showed significant differences at different timescales and a clear increasing trend along the E–W direction. This phenomenon was closely related to the increase in surface roughness and the blocking effect of sandy hills (Sankey et al., 2010; Aili et al., 2023; Liu et al., 2023a).

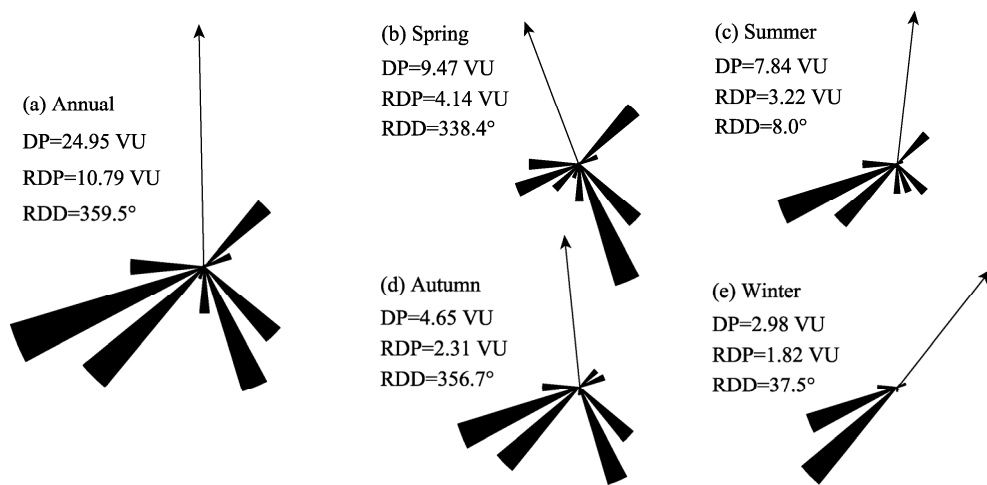


Fig. 6 Annual (a) and seasonal (b–e) roses of DP at site D. DP, drift potential; RDP, resultant drift potential. The arrow indicates the RDD.

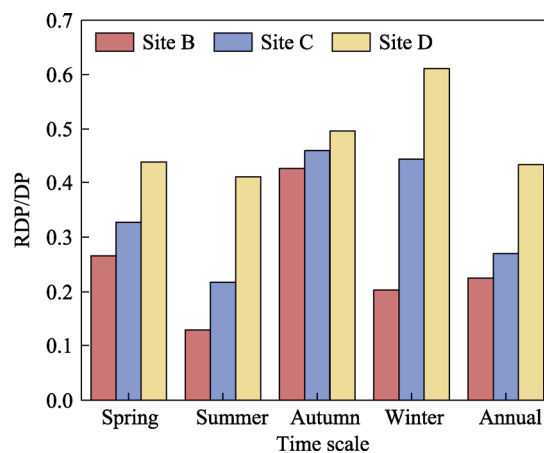


Fig. 7 Annual and seasonal RDP/DP at sites B, C, and D. RDP/DP, the ratio of RDP to DP, which is regarded as an important indicator for describing the directional variability of wind.

4 Conclusions

This study aims to fill the gap in our understanding of aeolian environment in the DOTZ and its key role in oasis protection by analyzing the near-surface wind field characteristics of the DOTZ in Dunhuang based on meteorological data from 2013 to 2019. The wind patterns within the DOTZ exhibited a distinct spatial gradient from W to E, characterized by low wind speed, low frequency of sand-driving wind, and low directional variability at the eastern site. Wind speed

was positively correlated with air temperature and was influenced by surface hydrothermal difference. The presence of sand hills, forests, and buildings on both sides of the DOTZ further modified the near-surface wind field, mitigating the impact of northwesterly wind while enhancing the influences of the wind from NE and SW. Hence, the prevailing winds in the region were from NE and SW. However, southeasterly wind primarily affected the adjacent areas of the oasis. Consequently, the near-surface wind field in the DOTZ was shaped by the combined effects of surface hydrothermal difference and local terrain. Generally speaking, the region showed a low wind energy environment. Compared with the desert, the oasis experienced significant reductions in the mean wind speed and annual number of sand-driving wind events by 64.98% and 82.75%, respectively. The fitting results of wind speed and air temperature for both the desert and oasis showed that air temperature was not the main factor influencing the wind speed variation from the desert to the oasis, but rather the effective blocking of the DOTZ. This caused the wind direction to exhibit relative uniformity in both areas, with southeasterly wind prevailing in the desert and easterly wind prevailing in the oasis. Therefore, the DOTZ acted as a vital buffer between the desert and oasis.

Although this study obtained some results regarding the near-surface wind field characteristics of the DOTZ in Dunhuang, there are still some scientific issues to be solved in the future. The first is to systematically analyze the impact of the DOTZ on the near-surface wind field characteristics of the desert and oasis, and the second is to design a suitable wind-blown sand control system to protect the oasis based on the aeolian environment of the DOTZ.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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